JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 98, NO. D5, PAGES 8683–8693, MAY 20, 1993

The Radiative Budgets of a Tropical Mesoscale Convective System During the EMEX-STEP-AMEX Experiment
1. Observations

TAKMENG WONG, GRAEME L. STEPHENS, AND PAUL W. STACKHOUSE, JR.

Department of Atmospheric Science, Colorado State University, Fort Collins

FRANCISCO P. J. VALERO

NASA AMES Research Center, Moffett Field, California

This paper is the first of a series of two that aim to describe the spatial and temporal variation of the radiative heating associated with tropical mesoscale convective systems (MCSs). This paper describes the analysis of data collected in and around a tropical cloud cluster system studied as part of the Equatorial Mesoscale Experiment (EMEX). The data analysis indicates that the cluster originated off the northern coast of Australia along the midlevel monsoon trough and lasted approximately 12 hours. The system moved with a velocity of about 12 m/s toward the northeast and the low-level surface northwesterly flow at the vicinity of the premonsoon trough area seems continuously to feed the EMEX 9 cloud cluster with energetic warm, moist equatorial air. Data obtained from aircraft penetrations show features similar to tropical MCSs reported elsewhere (such as an area of strong to moderate convection surrounded by a broad region of stratiform precipitation, radar echo bright band in the stratiform region, "onion" type sounding behind the convective region). The vertical structures of the EMEX 9 cloud cluster also contain two types of imbedded convection: an upright vertical structure and a pronounced rearward slope (approximately 17°), having a vertical extent of 14.5 km and above and a horizontal scale of about 40 km. The cloud base and cloud top altitude in the stratiform region are estimated to be of the order of 4.8 km and 15 to 16 km, respectively. The composite aircraft shortwave radiation data from the stratiform region show a significant attenuation of shortwave flux through the cloud (the estimated transmission is 14% at cloud base). The upward and downward solar flux profiles are almost parallel to each other in the atmosphere inside and below the cloud base, suggesting very little solar heating in these regions. The upward and downward infrared radiation fluxes measured in the tropical MCS also show little infrared heating above and below the cloud cluster.

1. INTRODUCTION

It is generally recognized that most of the weather occurring in the tropics is associated with the passage of the tropical mesoscale convective systems (MCSs) or the so-called tropical cloud clusters [*Hamilton and Archbold*, 1945; *Ramage*, 1971; *Houze*, 1976; *Simpson et al.*, 1988]. These systems, once formed, last several hours and are thought to provide significant impacts on the dynamics, thermodynamics, radiation, and the water budgets of the large-scale atmosphere [*Hartmann et al.*, 1984; *Cotton and Anthes*, 1989].

Composite studies from field experiments such as the Barbados Oceanographic and Meteorological Experiment (BOMEX), the Global Atmospheric Research Program's Atlantic Tropical Experiment (GATE), and Winter Monsoon Experiment (WMONEX) provide a conceptual idea of the structure of these tropical cloud systems [*Nitta and Esbensen*, 1974; *Zipser*, 1977; *Houze*, 1977; *Gamache and Houze*, 1982, 1983, 1985; *Houze and Rappaport*, 1984; *Churchill and Houze*, 1984]. From these studies the general view of tropical MCSs as characterized by a leading convective region (order of tens of kilometers) and a trailing mesoscale stratiform area (order of hundreds of kilometers) has emerged. The convective region contains active cumulonimbus cells with strong, small-scale, nonhydrostatic vertical motion [*LeMone*, 1983]. These cells tend to merge into the mesoscale region as they mature. The mesoscale region, on the other hand, fills with middle to upper tropospheric stratiform cloud in which gentle broad scale hydrostatic vertical motion exists [*Houze*, 1982]. Upward motion above the melting level is thought to be an important source for precipitation in the mesoscale region [*Rutledge*, 1986].

The net (latent plus radiative) diabatic heating associated with these tropical MCSs is an important source of energy for large-scale tropical motion [*Riehl and Malkus*, 1958; *Houze*, 1982; *Hartmann et al.*, 1984]. A number of studies [*Yamasaki*, 1969; *Lindzen*, 1974; *Chang*, 1976; *Stevens et al.*, 1977] of tropical storm movement and propagation based on wave-CISK theory indicate that the phase speed and the intensity of the tropical system are very sensitive to the initial profile of diabatic heating. *Houze* [1982, 1989], using a composite vertical motion field and a very crude radiative heating profile of a composite tropical MCS, estimated that the net diabatic heating associated with a typical tropical MCSs is greater above 600-mbar. This estimate, however, is somewhat inconclusive due to uncertainty in the vertical structure associated with the composite vertical motion field. The exact shape of this diabatic heating profile still remains as one of the important research topics in tropical meteorology.

This paper is the first of a series of two (hereafter referred to as parts 1 and 2) that aim to describe the spatial radiation heating/budget (both solar and infrared) associ-

Paper number 92JD02515.
0148-0227/93/92JD-02515$05.00

ated with tropical MCSs and to investigate the change of this heating/budget through the life cycle of such a cloud system. The approach to this problem is to use a combination of cloud model simulations, radiation model simulations, analyses of observations obtained during the Equatorial Mesoscale Experiment (EMEX), the Stratosphere-Troposphere Exchange Program (STEP), and the Australian Monsoon Experiment (AMEX) and comparisons to other studies of similar tropical MCSs. The present paper provides an overview of the three observational field programs and the analysis of the EMEX-STEP-AMEX case study that is the focus of this particular study. These observations will be used to compare to the results of a cloud model simulation in part 2 [*Wong et al.*, this issue] where simulations of the total (solar plus infrared) radiative heating/budget during the mature phase of the tropical MCS are presented.

2. Overview of the Three Field Programs

The observational data used in this study derive from three different but overlapping field experiments conducted during January and February 1987 off the northern coast of Australia. The three programs are the Equatorial Mesoscale Experiment (EMEX), the Stratosphere-Troposphere Exchange Project (STEP), and the Australian Monsoon Experiment (AMEX). These programs provide a unique and valuable data set on the structure of maritime tropical MCSs, the larger-scale environment in which they form, and interactions between the two. Figure 1 offers a simplified and integrated view of these three field programs. EMEX provides measurements inside and below the cloud systems; STEP provides data at levels above the convection; and AMEX provides the synoptic conditions in which these cloud systems were imbedded. A brief description of each of these experiments is given.

2.1. EMEX

The aim of EMEX was to examine the net diabatic heating associated with equatorial cloud cluster systems by carefully documenting the vertical and the kinematic motion structures of these systems [*Webster and Houze*, 1991]. The experiment sought to test the hypothesis that evolved from both GATE and WMONEX, namely, that the vertical diabatic heating profile in tropical MCSs has a maximum in the middle to upper troposphere [*Houze*, 1989]. This proposal stems from the observational studies that condensational heating in the lower troposphere in the convective regions of the MCS is offset by the evaporation cooling and melting of precipitation in the stratiform mesoscale region. Reinforcement of the heating from condensation and freezing of moisture in both the convective region and the mesoscale area, in addition to the radiative heating in the widespread stratiform clouds, is thought to produce a strong heating tendency in the middle to upper troposphere.

This idea could not be tested with the conventional synoptic sounding data network for the northern Australian region since the circulation and heating fields of the mesoscale cloud system could not be resolved by that network. Additional data platforms, and more extensive observational arrays, were thus provided during EMEX. The primary data source for the analysis of EMEX cloud clusters were obtained from aircraft, satellites, and from a ship platform.

Satellite observations provide time continuity and detailed information on the evolution of these tropical MCSs. These satellite data also provide information about the larger-scale environment in which these tropical MCSs were imbedded. Data from three satellites, the visible/infrared image data from the Japanese GMS 3 geostationary satellite and the visible/infrared AVHRR data from the NOAA 9 and NOAA 10 polar orbitary satellites, were archived for EMEX [*Stephens and Greenwald*, 1988].

The research vessel "Xianpyanghong 5" from the People's Republic of China was located at latitude 10.5° S and longitude 138° E during the entire EMEX period and provided vital atmospheric sounding information over the open ocean using conventional rawinsonde. On board the "Xianpyanghong 5" was the NOAA 74 C band 5-cm coherent radar to allow construction of both the Doppler wind profile and the radar reflectively field around the vessel. The ship radar data were limited since many of the tropical MCSs investigated during EMEX aircraft mission were located outside the range of the radar.

Three aircraft were used during the experiment: the NOAA WP-3, the NCAR Electra, and the Australian CSIRO F-27 [Gamache et al., 1987]. These aircraft facilities were the primary and most important data platform during EMEX since they can directly penetrate the maritime mesoscale cloud cluster systems. Flight plans of these aircraft were carefully constructed so that profiles of the vertical and kinematic motion in both the convective and the stratiform regions could be documented or determined as well as the radiative flux profiles in the mesoscale stratiform area. These aircraft were low-altitude platforms primarily used for probing the atmosphere below 8 km. Each aircraft was equipped with a suite of instruments to measure the dynamic, thermodynamic, and radiative properties of the atmosphere. In addition, Particles Measurement System

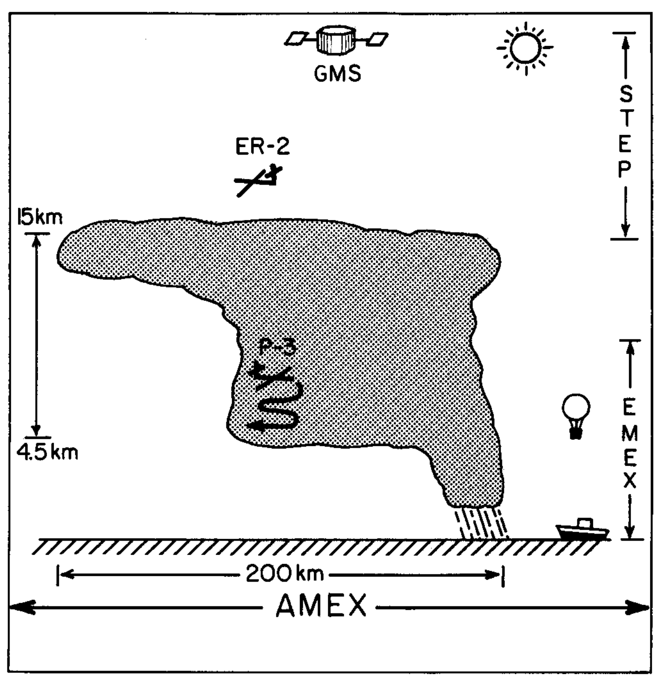

Fig. 1. A schematic of the synergism among EMEX, STEP, and AMEX.

(PMS) cloud microphysical measurements were also made on WP-3 and Electra. These PMS cloud microphysical data, however, have not been extensitively analyzed. The WP-3 was also equipped with a lower fuselage C band 5-cm noncoherent radar and a tail X band 3-cm coherent radar for both horizontal reflectivity scans (PPI) and vertical reflectivity scans (RHI), respectively. These radars provide a way of tracing and reconstructing cloud hydrometeors field at/near the aircraft's location as well as Doppler motion field of the atmosphere surrounding the aircraft itself.

A total of 10 research aircraft missions and 1 intercomparison calibration mission were conducted during EMEX between January 14 and February 4, 1987. A summary of these aircraft missions and the large-scale environmental condition during the entire EMEX experiment can be found in the work of *Webster and Houze* [1991].

2.2. STEP

The NASA STEP was an experiment designed to measure the physical and chemical properties in the tropopause region of the atmosphere and to understand the mechanisms that contribute to the chemical transports between the upper troposphere and the lower stratosphere. A key physical process under investigation concerns the role that cirrus anvil clouds play, if any, in the drying of the lower stratosphere [i.e., *Danielson*, 1982]. To investigate these processes, the NASA ER-2 aircraft, which was equipped with instruments that provided dynamical, thermodynamical, radiative, and cloud microphysical measurements of the upper troposphere and lower stratosphere, was used. Only the radiative data from ER-2 are used in this study to provide estimates of the upper level radiative boundary conditions at infrared wavelengths. Among the radiative instruments on the ER-2 are two broadband solar pyranometers (0.3-3.0 μm) and one rotating net flux infrared (4-40 μm) pyrgeometer. The pyranometers were located at the top and bottom of the fuselage to measure the downward and upward solar fluxes, respectively. These shortwave instruments, however, were mounted at an angle relative to the aircraft's plane of reference which makes the calibration correction somewhat difficult. The net infrared instrument protruded from the rear of one wing. These radiometers allow the calculation of heating rates in various layers of the atmosphere within or above the cloud top of the cirrus anvils. The ER-2 flew step flight paths at several different altitudes ranging from cloud top to the lower stratosphere between approximately 16 and 20 km.

2.3. AMEX

AMEX was a field experiment designed to study the Australian monsoon system during the northern winter and to improve the understanding on the interactions between the large-scale circulation and the maritime convection that occurs during the monsoon period [*Holland et. al.*, 1986]. These tropical MCSs are generally characterized by convective cloud bands and rainy weather. They are also formed in a region of lower tropospheric westerlies. This program was sponsored by the Australian Bureau of Meteorology Research Center (BMRC) for the period between January 10 and February 14, 1987.

In addition to the normal sounding stations a special sounding and surface synoptic network (reported every 4 hours) was established so that the weather systems in the Australian monsoon could be documented and the interaction between the cloud clusters and the large-scale flow diagnosed. Besides these observations, temperature and wind data retrieved from satellite and aircraft data were also collected and included in an objective analysis scheme provided by the BMRC to produce a set of synoptic data fields with 1.25° resolution for the entire AMEX period. Other data collected during AMEX also included information from the conventional ground-based noncoherent radar from Darwin, Gove, and Weipa.

3. LARGE-SCALE ENVIRONMENT OF THE EMEX 9 CASE STUDY

This study focuses on a MCS that developed during EMEX mission 9 between February 2 and 3, 1987. On February 2, 1987, a cloud cluster system was observed to move into the observational area of EMEX off the northern Australian coast. All four aircraft (WP-3, Electra, F-27, and ER-2) were dispatched into the area to document the cloud cluster system. This aircraft mission provided an excellent opportunity for studying the radiative budgets of the tropical mesoscale convective system. In this and the following section we will describe and analyze both the large-scale observations (i.e., AMEX synoptic data and EMEX satellite measurements) and the in-cloud measurements (i.e., EMEX and STEP aircraft data) associated with this cloud cluster system. The information obtained below will be used to set up and to verify the numerical cloud simulation in part 2 of this paper.

3.1. The Large-Scale Environment

The synoptic conditions prevailing over the AMEX area at 2300 UTC (0916 LST), February 2, 1987, are presented in Figures 2*a* and 2*b* in the form of the 500-mbar streamline and geopotential height field. The significant features of these fields are the strong cyclonic vortex associated with tropical cyclone Damina located off the west coast of Australia, the strong anticyclonic New Guinea vortex [*Webster and Houze*, 1991] stationed off the west coast of New Guinea island, and a strong midlevel westerly monsoon trough that extends from the northern Australian continent and across into New Guinea. This intense midlevel monsoon trough extended to the surface and presumably provided the necessary lifting mechanism for the formation of the MCS identified as the EMEX 9 cloud cluster. The large-scale synoptic vortex pair, the New Guinea anticyclone, and the Australian low or tropical cyclone, was also a common feature during other EMEX missions. The strength and location of these vortices may be strongly correlated to the beginning of the strengthening monsoon westerlies and the inception of the mesoscale convective activities during EMEX [*Webster and Houze*, 1991].

The wind profile north of the Gulf of Carpentaria is dominated by lower-level westerlies backing (counterclockwise rotation) with height into stronger easterlies aloft. This is apparent when the surface and the 100-mbar streamlines, shown in Figure 2*c* and 2*d*, are compared. Wind speeds exceeding 40 knots exist in the upper troposphere. In the vicinity of the premonsoon trough (i.e, region to the west of the monsoon trough), low-level surface northwesterly flow

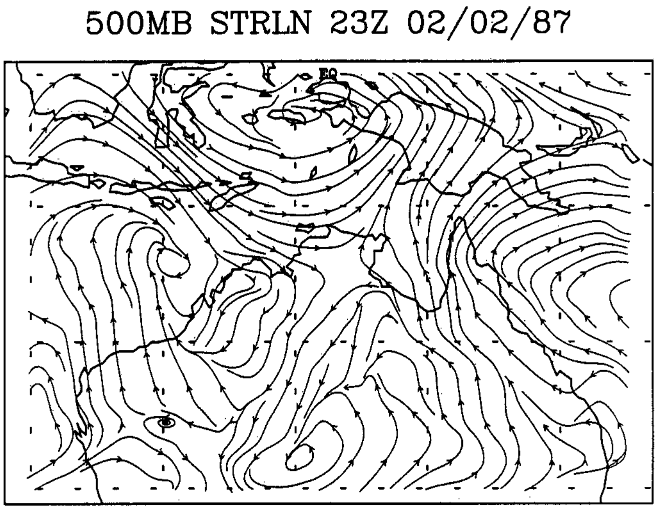

Fig. 2*a*. The 500-mbar streamline pattern at 2300 UTC on February 2, 1987 over the AMEX region.

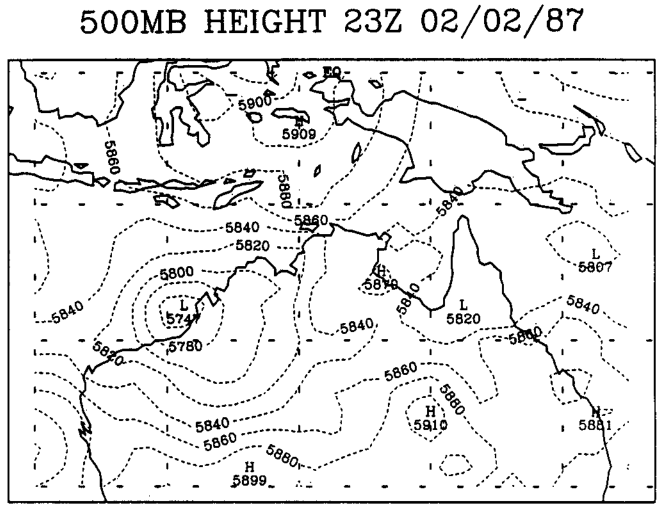

Fig. 2*b*. Same as Figure 2*a* but for the 500-mbar geopotential height field.

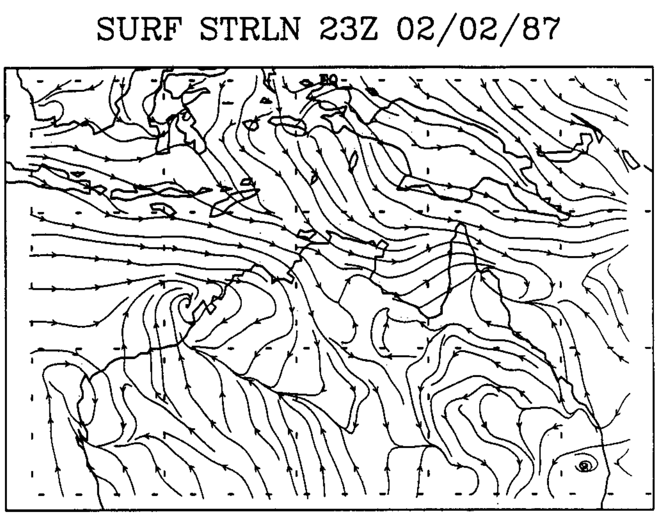

Fig. 2*c*. Same as Figure 2*a* but for the surface streamline pattern.

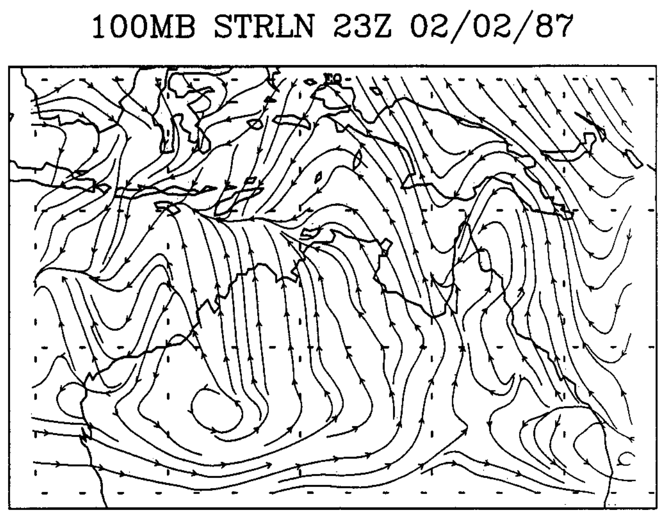

Fig. 2*d*. Same as Figure 2*a* but for the 100-mbar streamline pattern.

helped feed the cloud cluster with warm, moist equatorial air. The equivalent potential temperature field in Figure 2*e* has a minimum at 850-mbar surface located over the monsoon trough. We speculate that this feature results directly from the presence of the cloud cluster which acts to warm and dry out the lower troposphere.

3.2. Satellite Image Analysis of the Cloud Life Cycle

The series of enhanced infrared GMS satellite images shown in Figure 3 provides a sense of the life history of the EMEX 9 MCS. The image of Figure 3*a* suggests that the EMEX 9 cloud cluster originated off the northern coast of Australia along the midlevel monsoon trough before 1530 UTC (0146 LST) on February 2, 1987. This early morning development in mesoscale cloud system is a typical nocturnal characteristic of this oceanic region, which lies between the land masses of the maritime continent [*Williams and Houze*, 1987]. This cloud cluster system propagated along the monsoon trough and lasted for approximately 12 hours. The estimated speed and direction of propagation of the system, based on cloud motion analysis from these satellite

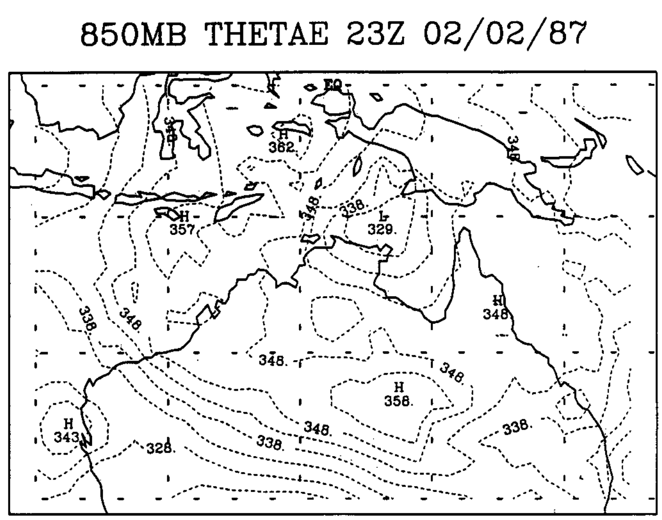

Fig. 2*e*. Same as Figure 2*a* but for the 850-mbar equivalent potential temperature field.

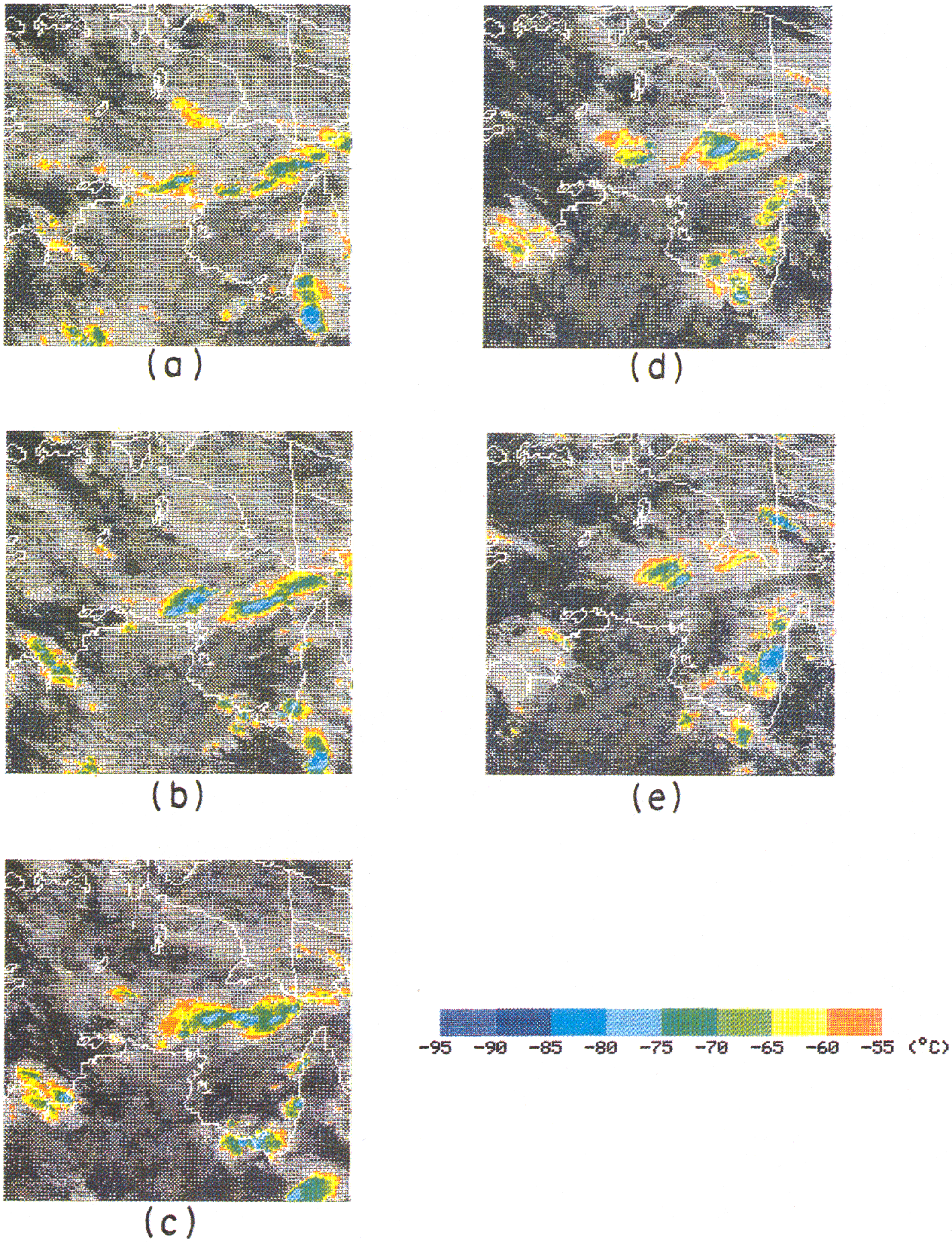

Fig. 3. GMS infrared satellite image at (*a*) 1530 UTC, February 2, 1987, (*b*) 1730 UTC, February 2, 1987, (*c*) 2030 UTC, February 2, 1987, (*d*) 2330 UTC, February 2, 1987, and (*e*) 0230 UTC, February 3, 1987 over the EMEX region. Cloud tops colder than -55° C are enhanced in the image.

images, is about 12 m/s toward the northeast. The MCS was fully developed by 1730 UTC (0346 LST), as suggested by the broad area of cold cloud top temperatures in Figure 3*b*, and had moved out into the open ocean. Cloud cluster scale interactions are evident in the 2030 UTC (0646 LST) image (Figure 3*c*) as the EMEX 9 cloud cluster merged with another cluster that had formed in the Gulf of Carpentaria. This merger seems to enhance the circulation in the MCS, as indicated by the extensive area of cold cloud top temperature, and presumably extends the life cycle of the convection. This particular cluster-cluster interaction is not investigated in this study and the model simulation in part 2 of this paper is only of the earlier phase of the MCS. At 2330 UTC (0946 LST), shown in Figure 3*d*, the EMEX 9 cloud cluster is centered at latitude 9° S and longitude 139° E with a minimum recorded cloud top temperature less than -70° C. According to the Darwin temperature sounding data taken at 2300 UTC, this cold cloud top temperature indicates that the vertical extent of this cloud system had penetrated well into the 150-mbar (15 km) height surface. Furthermore, the satellite data reveal an extended area of cirrus cloud in the cloud cluster with cloud top temperatures less than -60° C. The EMEX 9 cloud cluster had slowly decayed by 0230 UTC (1246 LST) on February 3, 1987 (Figure 3*e*) as it approached the coastal area of New Guinea island.

4. EMEX 9 AIRCRAFT DATA

Aircraft measurements collected during EMEX 9 provide important information on the vertical motion, kinematic structures, and radiation profile within maritime tropical monsoon cloud systems. In the following sections we will discuss the findings concerning the insitu data from the radiation sounding period and the Doppler radar data from the convective/transition and the stratiform period of the aircraft mission.

4.1. Data From Convective/Transition and Stratiform Period

The determination and documentation of the vertical motion and kinematic structure in both the convective and the stratiform region of the tropical MCSs is the most important objective of the EMEX experiment. This objective was accomplished through the use of airborne Doppler radar system on the NOAA WP-3 aircraft. During the convective/transition and stratiform periods of the aircraft mission the WP-3 flight plan calls for a series of Doppler legs flight pattern, which flies back and forth at 60° angle with each other directly across the area of interests. The advantage of this special pattern is that it allows for reconstruction of the temporal composite pseudodual Doppler wind fields as well as produces a temporal composite of the vertical velocity profile. For EXEM 9 this flight pattern was performed at an altitude of about 5 km. The discussion below is a brief summary of the results published by *Webster and Houze* [1991] on the Doppler data collected from WP-3 aircraft during the convective/transition period (2040 to 2201 UTC) and the stratiform period (2302 to 2350 UTC) on February 2, 1987. These results are presented here as they are relevant to our model simulations described in part 2 of this paper.

The noncoherent lower-fuselage radar data collected for the EMEX 9 cloud cluster during the convective/transition period showed regions of strong to moderate convection surrounded by a broad area of stratiform precipitation. The WP-3 vertical incidence Doppler radar reflectivity data recorded from the tail radar during this period indicated two types of imbedded convection associated with this cloud cluster system: an upright vertical structure (illustrated in Figure 4*a*) and a pronounced rearward slope (shown in Figure 5*a*). The angle of this rearward sloping convection is about 17°. Both of these types of convection extend up to 14.5 km and above and have a horizontal scale of about 40 km according to the figures. The vertical motion fields retrieved from the incidence Doppler velocity data showed that the upright convection was composed of relatively weak upper level upward and downward motion fields (shown in Figure 4*b*). The vertical motion fields for the pronounced rearward sloping convection (shown in Figure 5*b*), on the other hand, possesses much stronger updrafts. The maximum updraft for this squall-line-like convection is found at about 10 km. Strong downdrafts are also present in the lower troposphere ahead of the strong updraft aloft and are a feature characteristic of a sloping system. The contrasting radar data collected during the stratiform precipitation period is shown in Figure 6. In comparison to the convective region the radar reflectivity data in the stratiform region indicate a relatively more uniform precipitation field with a bright band echo region near the freezing level (between 4 and 4.5 km), which are typical features to both tropical and

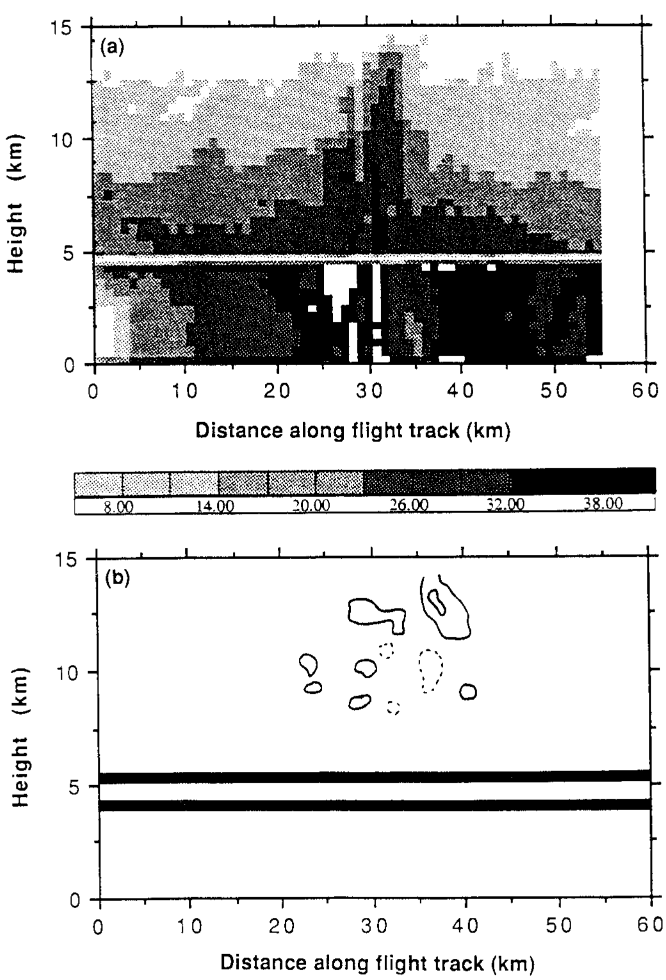

Fig. 4. Time-height section of vertically pointing data from the NOAA WP-3 tail radar for the convective region of EMEX 9 cloud cluster showing upright vertical structure. (*a*) Radar reflectivity (dBZ) and (*b*) Doppler vertical velocity of precipitation particles (m/s: solid contours +1, +3; dashed contour -4). From *Webster and Houze* [1991].

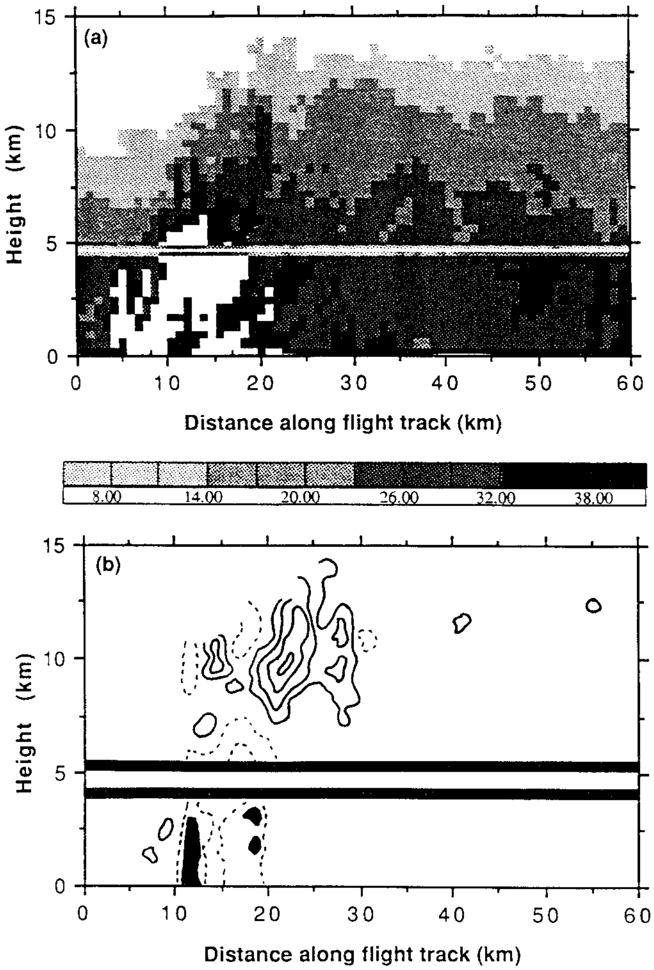

Fig. 5. Time-height section of vertically pointing data from the NOAA WP-3 tail radar for the convective region of EMEX 9 cloud cluster showing pronounced rearward slope. (*a*) Radar reflectivity (dBZ) and (*b*) Doppler vertical velocity of precipitation particles (m/s: solid contours +1, +3, +5, and +7; dashed contour -4 (above melting level only), -10; filled areas < -12 m/s). From *Webster and Houze* [1991].

mid-latitude mesoscale cloud system [i.e., *Houze*, 1977; and *Srivastava et. al.*, 1986].

4.2. Data From the Radiation Sounding Period

Estimation of the total (solar plus infrared) radiation budget in the widespread stratiform region of the cloud system was another primary objective of EMEX. EMEX proposed to accomplish this, in part, using measurements from the WP-3 aircraft operating in a special radiation survey pattern. This flight pattern consists of 5 min straight and level legs of approximately 40 km in length flown in a stairstep fashion, with each leg directly below the previous one. Since the entire radiation sounding flight pattern took approximately 1 hour to complete, the aircraft measurements at each level were actually taken at slightly different locations to account for cloud cluster movement during this period. Insitu data collected by the aircraft during this radiation sounding period are used in this study to reconstruct the mean vertical profiles of radiation, dynamic, and thermodynamic fields of the atmosphere in and below the stratiform cloud region by assuming that the structures of the stratiform cloud remained relatively unchanged over the entire 1-hour sounding period. This assumption is not always upheld since solar insolation varied during the period of the sounding although its validity may be reasonable in the dynamically weak stratiform region. The WP-3 flight pattern during EMEX 9 began at the highest altitude of 6.8 km at 0026 UTC (1042 LST) and ended at about 1.3 km at 0117 UTC (1133 LST) on February 3, 1987. The data collected during this time represents atmospheric conditions of the stratiform region during the later stage in the life cycle of the EMEX 9 cloud system. Only the radiation fields in and below the stratiform cloud were measured by the WP-3. Radiation fields above cloud top measured by the NASA ER-2 aircraft were used to complete the cloud radiation budgets in the stratiform region.

Figure 7 provides a composite of the vertical profile of the observed dynamical and thermodynamical fields averaged over each flight leg during the WP-3 radiation survey period in the stratiform region of the EMEX 9 cloud cluster. The temperature and dew point profiles show a typical "onion" type sounding found to the rear of the convective system. This onion type sounding is a consequence of the subsidence warming below the cloud base which tends both to warm and to dry the air and therefore amplify the separation between the temperature and the dew point curves in the sounding [*Zipser*, 1977]. The cloud base altitude at 4.8 km is determined when the air at a particular level is completely saturated with respect to the ambient air temperature in the WP-3 sounding. The cloud top altitude is estimated from matching the Darwin temperature sounding data with the GMS cloud top infrared brightness temperature and is determined to be between 15 and 16 km. A middle to low-level rear to front flow is also observed in the mean sounding with a maximum value of 19 m/s at about 750-mbar. This flow is consistent with early findings by *Johnson and Hamilton* [1988] and by Doppler radar data for mid-latitude MCS. The mean vertical profile of vertical velocity field (solid line in Figure 7*b*), calculated from both the WP-3 aircraft's vertical acceleration and the navigation data, shows downward vertical motion at and below the melting level (4.8 km) and upward vertical motion 2 km above this level. This is also consistent with the results derived from GATE and winter MONEX [i.e., *Houze*, 1982; *Johnson*, 1982]. The effects of the downward motion below the freezing level are also evident in the mean temperature sounding in Figure 7*a*. The lapse rate below the cloud base in Figure 7*a* lies somewhere between a dry and moist adiabat which is indicative that mixing of moist cloud air with drier environmental air below the cloud base has occurred as air slowly descends below the freezing level. The mean vertical profile of cloud liquid water content obtained with the Johnson-Williams hot wire probe is also shown in Figure 7*b* (dashed line). This profile indicates that cloud liquid water generally increases with height to the freezing level and slowly decreases above this level as water freezes to form ice particles. The maximum cloud liquid water content recorded in the stratiform region is of the order of 0.4 g/m^3.

Figure 8 presents a composite of the radiation measurements averaged over each flight leg. Because of the variation of the solar fluxes with time due to changes in the solar elevation the solar fluxes are normalized relative to the mean time of the WP-3 radiation profile at 0050 UTC (1106 LST) on February 3, 1987. We performed this normalization using

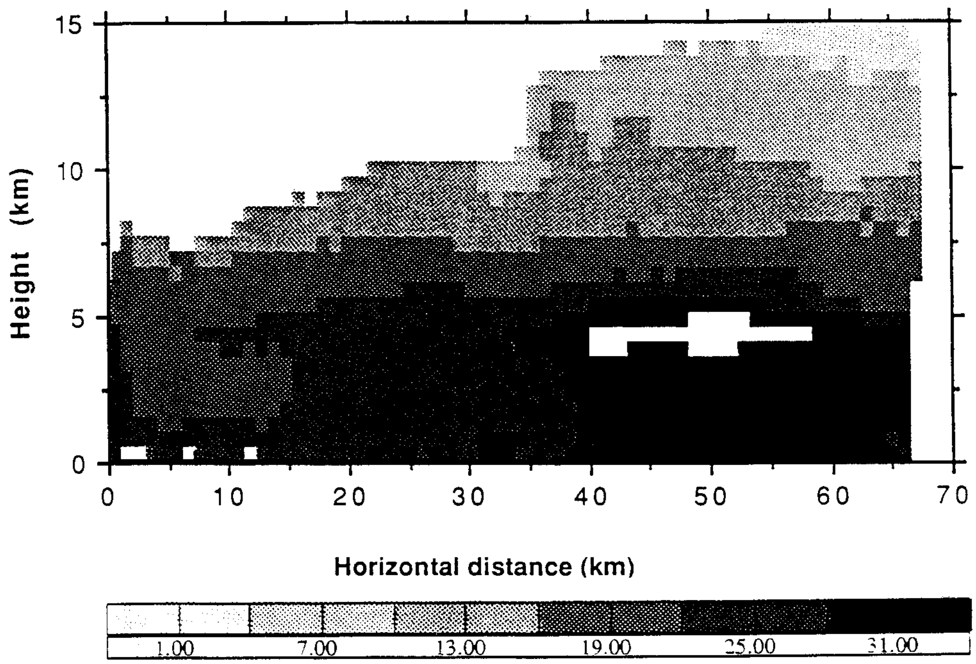

Fig. 6. Vertical cross section of radar reflectivity (dBZ) from the NOAA WP-3 for the stratiform region of EMEX 9 cloud cluster showing relatively uniform horizontal structures. From *Webster and Houze* [1991].

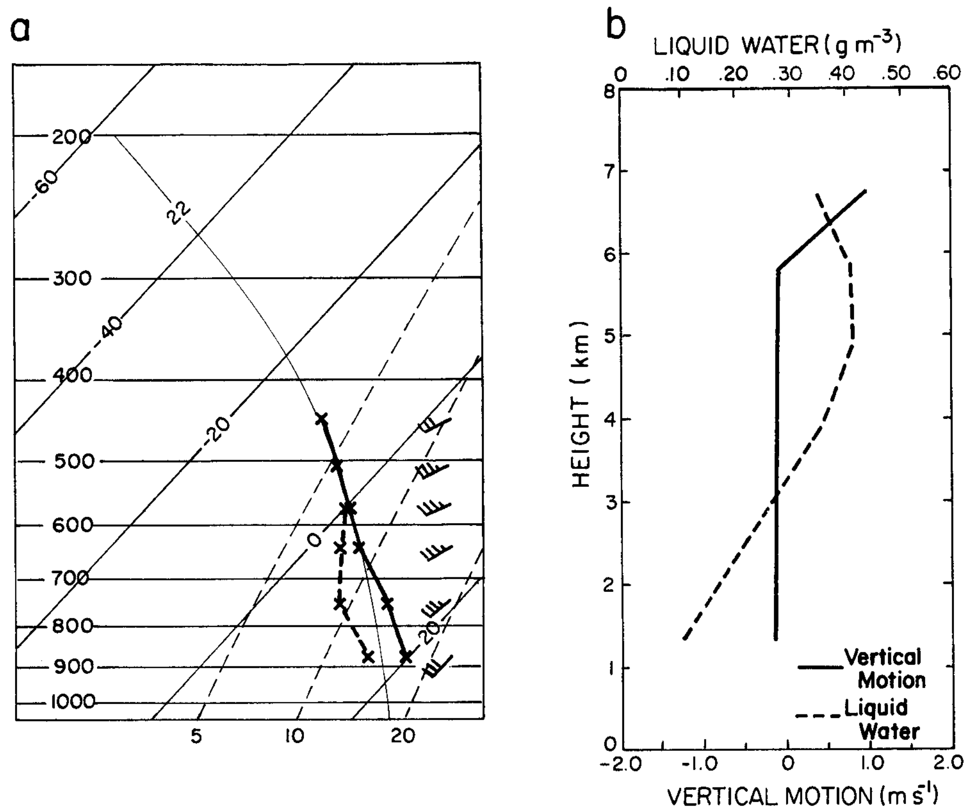

Fig. 7. The reconstructed vertical profiles of (*a*) temperature (solid), dew point (dashed), and horizontal wind field (wind bar) and (*b*) vertical motion (solid) and liquid water content (dashed) in the stratiform region of EMEX 9 cloud cluster from the NOAA WP-3 aircraft.

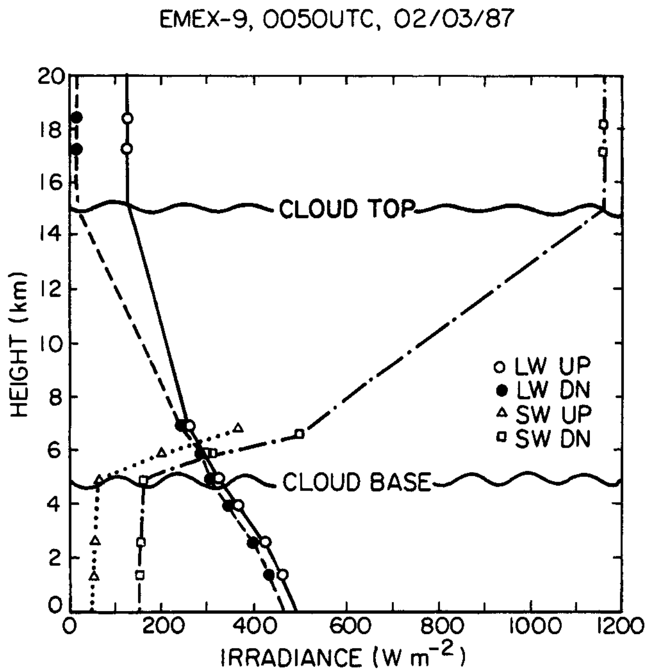

Fig. 8. The reconstructed vertical profiles of the observed radiation fields (infrared and shortwave) in the stratiform region of the EMEX 9 cloud cluster from the NOAA WP-3 and the NASA ER-2 aircraft. The solar measurements are normalized to 0050 UTC on February 3, 1987. The actual radiation observations are given by various symbols (i.e., open circle for upward infrared flux, solid circle for downward infrared flux, triangle for upward shortwave flux, and square for downward shortwave flux) on the graph. Simple linear interpolation and extrapolation schemes have been used to connect the data points on the graph together (i.e., solid line for upward infrared flux, dashed line for downward infrared flux, dotted line for upward shortwave flux, and dotted-dashed line for downward shortwave flux).

an appropriately chosen factor that relates the ratio of the cosine of the solar zenith angle at the time of observation to the cosine of the solar zenith angle at 0050 UTC (1106 LST). While the measurements above the cloud top were taken by the NASA ER-2 high-altitude aircraft above altitudes of 16 km, the measurements inside and beneath the tropical MCS at altitudes below 7 km were obtained from the NOAA WP-3 aircraft between 0026 and 0117 UTC. Cloud top and cloud base level were determined from methods mentioned above. There are no data in the region between 7 and 16 km and a simple linear interpolation is used merely to connect the data. A linear extrapolation is also applied to extend radiation profiles to the surface. The shortwave radiation measurements from the ER-2 are not used in this composite due to calibration problem with the shortwave instrument as mentioned in the earlier section. Instead, the two-stream radiation model discussed in part 2 of this paper is used to give the best estimate of the downward flux of shortwave radiation at cloud top.

The shortwave analysis values indicated on Figure 8 shows a significant attenuation of shortwave flux through the cloud (the estimated transmission is 14% at cloud base for the example shown). The upward and downward solar flux profiles are almost parallel to each other in the atmosphere inside and below the cloud base, suggesting very little solar heating in these regions. The upward and downward infrared radiation fluxes measured in the tropical MCS also show features similar to those of the solar fluxes. We infer little infrared heating above and below the cloud since the upward and downward infrared profiles are approximately parallel to each other. The measured infrared fluxes are also close to the blackbody fluxes in the region from 4.8 to 6.8 km, but the upward and downward fluxes diverge at levels both above and below the inner blackbody layer of the cloud. Unfortunately, the level at which the profiles diverge from the blackbody profile could not be estimated from the data and therefore we cannot estimate from observations the depth to which the longwave cooling penetrates into cloud top or the height to which longwave heating extends above the cloud base. However, the data do suggest the expected general trend of cloud top infrared cooling and cloud base longwave heating. The upward calculated infrared flux at the cloud top is associated with brightness temperature of about -60° C which is broadly consistent with the GMS infrared satellite brightness temperature from 2300 and 0230 UTC. There is also significant variability in the radiation data (not shown). The solar fluxes vary more than infrared fluxes since they are more sensitive to the broken cloudiness.

5. SUMMARY

This paper describes the analysis of observations collected during EMEX mission 9 of a tropical cloud cluster which occurred during the EMEX-STEP-AMEX experiments on February 2 and February 3, 1987, over the Gulf of Carpentaria off the northern coast of Australia. The gross features of the mesoscale cloud system and the large-scale environment in which it forms include the following:

1. The large-scale weather pattern over the AMEX region for this case study is dominated by the strong cyclonic vortex of tropical cyclone Damina off the west coast of Australia, a strong vortex over the west coast of New Guinea, and a strong midlevel westerly monsoon trough that extends from the northern Australian continent and across into New Guinea. The large-scale wind profile in the region is marked by lower-level westerlies backing with height into stronger easterlies aloft. Low-level surface northwesterly flow in the vicinity of the premonsoon trough area seems to continuously feed the EMEX 9 cloud cluster with energetic warm, moist equatorial air. A minimum in equivalent potential temperature field at 850-mbar in the synoptic data also suggests the warming and drying effects produced with this tropical cloud system.

2. The satellite image time series analysis of the cloud system life cycle for this case suggests that the EMEX 9 cloud cluster originated off the northern coast of Australia along the midlevel monsoon trough during early morning hours. The cloud cluster then propagated along the monsoon trough with system velocity of about 12 m/s toward the northeast. Cloud cluster scale interactions are also evident during this period as the EMEX 9 cloud system merged with another cluster that formed in the Gulf of Carpentaria. The mature stage of the system possesses an extended area of cirrus cloud well above 15 km.

Aircraft measurements within the cloud system revealed the following properties of the MCS:

1. Aircraft radar data collected during the convective/transition regions of the cloud system show areas of strong to moderate convection surrounded by a broad region of stratiform precipitation. The vertical structures of the cloud hydrometeor fields and vertical air motion retrieved

from the vertical incidence Doppler radar data indicate two types of imbedded convection: an upright vertical structure and a pronounced rearward slope (approximately 17°), having a vertical extent in excess of 14.5 km and a horizontal scale of about 40 km. While the vertical motion fields for the upright vertical structured convection were composed of relatively weak upper level upward and downward motions, the vertical motions associated with the rearward sloping convection possess much stronger updrafts with maximum updraft located at about 10 km. Strong downdrafts are also present in the lower troposphere ahead of this strong updraft aloft and is a feature characteristic of a sloping system. In comparison to the convective region the radar reflectivity data in the stratiform region indicate a relatively more uniform precipitation field with a bright band echo region near the freezing level (between 4 and 4.5 km), which are typical features of both tropical and mid-latitude mesoscale cloud systems.

2. The composited vertical profiles of insitu thermodynamical parameters in the stratiform region show a typical "onion" type sounding to the rear of the convective system, which is a consequence of the subsidence warming and drying below the cloud base. The cloud base altitude at 4.8 km determined using insitu temperature and moisture data during this period is consistent with the radar bright band echo region.

3. The cloud top altitude in this region is estimated by matching the Darwin temperature sounding data with the GMS cloud top infrared brightness temperature and is determined to be between 15 and 16 km.

4. The mean vertical profile of cloud liquid water content indicates that cloud liquid water generally increases with height to the freezing level and slowly decreases above this level as water freezes to form ice particles. The maximum cloud liquid water content recorded in the stratiform region is of the order of 0.4 g/m^3.

5. A middle- to low-level rear to front flow is also observed in the mean sounding with a maximum value of 19 m/s at 750-mbar consistent with findings for mid-latitude MCS. The mean vertical profile of vertical velocity field shows downward vertical motion at and below the melting level (4.8 km) and upward vertical motion 2 km above this level. These results are also consistent with the earlier published results.

6. The composited shortwave analysis shows a significant attenuation of shortwave flux through the stratiform region of the cloud (the estimated transmission is 14% at cloud base). The upward and downward solar flux profiles are almost parallel to each other in the atmosphere inside and below the cloud base, suggesting very little solar heating in these regions. The upward and downward infrared radiation fluxes measured in the tropical MCS also show features similar to those of the solar fluxes. We infer little infrared heating above and below the cloud since the upward and downward infrared profiles are approximately parallel to each other.

Acknowledgments. The authors would like to acknowledge the NOAA National Hurricane Division for supplying the EMEX WP-3 insitu data set, the Australian Bureau of Meteorology Research Center for providing the AMEX objective analysis data set, Bill Thorson for use of his computer program in decoding the AMEX FGGE 3B data set, Brian Mapes for supplying the airborne Doppler data, Judy Dunn for drafting the figures, Heather Jensen and Susan Lini for formatting the manuscript. This research was supported in part by NSF grant ATM-8812353, NSF grant ATM-8617856, and NASA grant NAG-5-1122.

REFERENCES

Chang, C.-P., Vertical structure of tropical waves maintained by internally-induced cumulus heating, *J. Atmos. Sci.*, *33*, 729-739, 1976.

Churchill, D. D., and R. A. Houze, Jr., Development and structure of winter monsoon cloud clusters on 10 December 1978, *J. Atmos. Sci.*, *41*, 933-960, 1984.

Cotton., W. R., and R. A. Anthes, *Storm and Cloud Dynamics*, 883 pp., Academic, San Diego, Calif., 1989.

Danielson, E. F., A dehydration mechanism for the stratosphere, *Geophys. Res. Lett.*, *9*, 605-608, 1982.

Gamache, J. F., and R. A. Houze, Jr., Mesoscale air motions associated with a tropical squall line, *Mon. Weather Rev.*, *110*, 118-135, 1982.

Gamache, J. F., and R. A. Houze, Jr., Water budget of a mesoscale convective system in the tropics, *J. Atmos. Sci.*, *40*, 1835-1850, 1983.

Gamache, J. F., and R. A. Houze, Jr., Further analysis of the composite wind and thermodynamic structure of the 12 September GATE squall line, *Mon. Weather Rev.*, *113*, 1241-1259, 1985.

Gamache, J. F., F. D. Marks, Jr., and R. W. Burpee, EMEX data report, Hurricane Res. Div., Atlantic Oceanogr. and Meteorol. Lab., Miami, Florida, 1987.

Hamilton, R. A., and J. W. Archbold, Meteorology of Nigeria and adjacent territory, *Q. J. R. Meteorol. Soc.*, *71*, 231-262, 1945.

Hartmann, D. L., H. H. Hendon, and R. A. Houze, Jr., Some implications of the mesoscale circulations in tropical cloud clusters for large-scale dynamics and climate, *J. Atmos. Sci.*, *41*, 113-121, 1984.

Holland, G. J., J. L. McBride, R. K. Smith, D. Jasper, and T. D. Keenan, The BMRC Australian Monsoon Experiment: AMEX, *Bull. Am. Meteorol. Soc.*, *67*, 1466-1472, 1986.

Houze, R. A., Jr., GATE radar observations of a tropical squall line, *in Preprints of 17th Conference on Radar Meteorology, Seattle, Wash.*, 384-389, American Meteorological Society, Boston, Mass., 1976.

Houze, R. A., Jr., Structure and dynamics of a tropical squall-line system, *Mon. Weather Rev.*, *105*, 1540-1567, 1977.

Houze, R. A., Jr., Cloud clusters and large-scale vertical motions in the tropics, *J. Meteorol. Soc. Jpn.*, *60*, 396-410, 1982.

Houze, R. A., Jr., Observed structure of mesoscale convective systems and implications for large-scale heating, *Q. J. R. Meteorol. Soc.*, *115*, 425-461, 1989.

Houze, R. A., Jr., and E. N. Rappaport, Air motions and precipitation structure of an early summer squall line over the eastern tropical Atlantic, *J. Atmos. Sci.*, *41*, 553-574, 1984.

Jonhson, R. H., Vertical motion in near-equatorial winter monsoon convection, *J. Meteorol. Soc. Jpn.*, *60*, 682-690, 1982.

Johnson, R. H., and P. J. Hamiltion, The relationship of surface pressure features to the precipitation and air flow structure of an intense midlatitude squall line, *Mon. Weather Rev.*, *116*, 1444-1472, 1988.

LeMone, M. A., Momentum flux by a line of cumulonimbus, *J. Atmos. Sci.*, *40*, 1815-1834, 1983.

Lindzen, R. S., Wave-CISK in the tropics, *J. Atmos. Sci.*, *31* 156-179, 1974.

Nitta, T., and S. Esbensen, Heat and moisture budget analyses using BOMEX data, *Mon. Weather Rev.*, *102*, 17-28, 1974.

Ramage, C. S., *Monsoon Meteorology*, 296 pp., Academic, San Diego, Calif., 1971.

Riehl, H., and J. S., Malkus, On the heat balance in the equatorial trough zone, *Geophysica*, *6*, 503-538, 1958.

Rutledge, S. A., A diagnostic modeling study of the stratiform region associated with a tropical squall line, *J. Atmos. Sci.*, *43*, 1356-1377, 1986.

Simpson, J., R. F. Adler, and G. R. North, A proposed tropical rainfall measuring mission (TRMM) satellite, *Bull. Am. Meteorol. Soc.*, *69*, 278-295, 1988.

Srivastave, R. C., T. J. Matejka, and T. J. Lorello, Doppler radar study of the trailing anvil region associated with a squall line, *J. Atmos. Sci.*, *43*, 356-377, 1986.

Stephens, G. L., and T. J. Greenwald, An atlas of the satellite observations during the EMEX aircraft missions, *Dep. of Atmos. Sci., Colo. State Univ.*, Fort Collins, 1988.

Stevens, D. E., R. S. Lindzen, and L. J. Shapiro, A new model of tropical waves incorporating momentum mixing by cumulus convection, *Dyn. Atmos. Oceans*, *1*, 365-425, 1977.

Webster, P. J., and R. A. Houze, Jr., The Equatorial Mesoscale Experiment (EMEX): An overview, *Bull. Am. Meteorol. Soc.*, *72*, 1481-1505, 1991.

William, M., and R. A. Houze, Jr., Satellite-observed characteristics of winter monsoon cloud cluster, *Mon. Weather Rev.*, *115*, 505-519, 1987.

Wong, T., G. L. Stephens, P. W. Stackhouse, Jr., and F. P. J. Valero, The radiative budget's of a tropical mesoscale convective system during EMEX-STEP-AMEX experiment, 2, Model results, *J. Geophys. Res.*, this issue.

Yamasaki, M., Large-scale disturbances in the conditional unstable atmosphere in low latitudes, *Pap. Meteorol. Geophys.*, *20*, 298-336, 1969.

Zipser, E. J., Mesoscale and convective-scale downdrafts as distinct components of squall line structure, *Mon. Weather Rev.*, *105*, 1568-1589, 1977.

T. Wong, G. L. Stephens and P. W. Stackhouse, Jr., Department of Atmoshperic Science, Colorado State University, Ft. Collins, CO 80523.

F. P. J. Valero, NASA AMES Research Center, Moffett Field, CA 94035.

(Received September 9, 1991;
revised October 16, 1992;
accepted October 16, 1992.)